

Utilizing Heavy-Ion Fragmentation in an ISOL Facility

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A key feature of the Argonne ISOL concept is the use of intense energetic heavy-ion beams with projectile fragmentation as a production mechanism for beams of short-lived nuclei. This method, based on in-flight fragment separation, stopping of the fragments as singly-charged ions in an IGISOL-type helium gas cell configuration, and fast extraction, allows for a breakthrough in capabilities for a broad range of beams.

The scheme combines the intrinsic advantages of in-flight fragmentation, short delay times, with those of the ISOL concept, high-quality beams of precise energy as required by experiments. The techniques are well established due to extensive past work with both fragment separators and the IGISOL technique. This is illustrated with two examples, the production of beams of ^{14}Be and ^{44}S , beams that become very feasible ($>10^6/\text{s}$) and are very difficult (at best a few 100/s) with the standard thick-target ISOL configuration.

Overview of concept

The ISOL method relies on the production of radioactive isotopes in a heated thick target. The isotopes diffuse out of the target and migrate to an ion source out of which a low-energy radioactive beam is extracted. The major stumbling block in the ISOL method is the need to rapidly and efficiently move the isotopes from within the target to the ion source. Chemical properties limit the number of elements for which this can be done efficiently for short-lived isotopes (say with a total efficiency above 0.1% for isotopes with a half-life below 10 seconds) to less than one third of the elements. And the extraction efficiency for isotopes with shorter half-lives drops further, even for those few elements with "good" chemical properties. A solution to this problem is provided by the ion guide technique or IGISOL, where isotopes produced in a thin target are stopped in a gas and extracted quickly (order of ms) by the gas flow. This method provides fast and efficient extraction, independent of the chemical properties of the isotopes of interest, but has been limited to low yields because of the thin targets required by the production mechanisms available. The high-energy heavy-ion beam driver proposed for the ANL ISOL facility opens up the possibility of merging IGISOL techniques and their universal properties together with the thick target production intensities of the fragmentation mechanism.

The high intensity 100 MeV/u heavy-ion beam impinges on a moderately thick target of cooled light material (liquid-lithium cooled graphite or pure liquid lithium) where the fragmentation products are produced. The kinematics pushes all reaction products in a narrow forward cone where they are collected by a large-acceptance fragment separator, separated from the bulk of the reaction products, and their energy dispersion is reduced before they are slowed down at the entrance of a gas cell. It is important that the primary beam not enter the gas cell, otherwise the high ionization density creates a plasma that affects the recoil ions. For neutron-rich isotopes this can be avoided just by ranging out the primary beam in a sufficiently thick primary target. A more general solution involves the use of a high acceptance fragment separator which removes not only the beam but a large fraction of the other fragments also produced in the projectile fragmentation process. The transmitted recoils, after a system of shaped absorbers in the fragment separator, lose their residual energy in the high-purity helium of the gas cell, recapturing electrons during the deceleration until they come to rest. The vast majority of them will be in the singly ionized charge state due to the

high ionization potential of atomic helium. They are then pulled out of the gas cell by electric fields applied inside the cell and the gas flow itself which becomes dominant as the ions approach the exit aperture. The electric fields are used to increase the speed with which the ions are extracted from the cell (typically milliseconds) beyond that from just using the gas flow. This scheme maintains the fast properties of IGISOL systems with the larger gas cell required to stop the fragmentation products. The ions extracted from the gas cell are transported by an rf structure to a region of lower pressure from where they are accelerated in a fashion similar to a standard IGISOL system. The scheme was successfully demonstrated experimentally, with a gas-stopper/ion guide system at the Penning trap (CPT) at ATLAS.

In the following the different components will be described in more detail and two specific examples will be used to illustrate the potential of the technique. A broad range of beams based on this technique is given in the Argonne beam list and some examples of the exciting physics issues that become accessible are described at the end of this document.

Properties of a proposed fragment separator

The fragment separator is shown schematically in figure 1. It ensures that the primary beam not reach the gas cell, even for isotopes on the neutron-deficient side that do not outrange the primary beam. It selects the relevant portion of the reaction products, eliminating the issue of ionization in the gas, and eliminates the very light particles (protons, alphas, etc.). This can be done at only a small loss in efficiency (which is somewhere between 70% for the best cases and down to about 20%.)

The separator requires a high momentum acceptance to allow operation with thick targets, a moderate angular acceptance because of the kinematics of the fragmentation process, and only very limited mass resolution. A solution for a recoil separator with $dp/p = 10\%$ and an angular acceptance of 100 mr has been worked out. It is similar to existing recoil separators and presents little in the way of technological risks. The target is followed by large aperture focusing elements before a large magnetic sector which then takes the beam through more focusing elements to an intermediate focal point where a wedged degrader is located. Recoil selection is obtained at that point by dE/dx selection with the second part of the separator (a mirror image of the first part) tuned to transport the selected degraded fragments to the focal point. The device is achromatic (the wedge shape of the degrader at the intermediate focal point is needed to maintain achromaticity when the degrader is used) and has a mass resolution of about 100. At that point the fragments go through a simple section composed of a magnet (dispersion of about 1 cm/%) to disperse the recoils in energy, a wedge to cancel out the energy spread, and finally a quadrupole doublet to get a circular spot size of about 3 cm diameter, which then goes through a final degrader before entering the gas cell.

The separator under consideration has sufficient selectivity to work with radioactive fragments very close to the primary beam. Its estimated cost is about \$8M. A simpler separator consisting of a magnet followed by a wedge and a quadrupole magnet and costing \$1-2M can suppress most of the unwanted activities and remove the energy spread in the fragments.

Design and prototype results for the active gas cell

The gas cell catcher is shown in figure 2. It has a length of about 50 cm and can be operated at pressures, depending on the fragments to be observed, varying from 1 to 10 atmospheres. An electric gradient along the length of the cell will drag the radioactive ions stopped in the gas towards the cell exit where a set of concentric electrodes will help focus them on the exit hole. At the exit hole, the gas velocity grows rapidly and pulls the ions out. The voltage gradients required to extract the ions in ms timescales can be determined from ion

mobility data. The proposed gas cell and a scaled down 15 cm prototype operating at up to 0.5 atmosphere have been designed using an ion trajectory program on which the effect of the gas is added by simulating the gas collisions adjusted to reproduce the known ion mobility. The scaled down version of the gas cell has been constructed at Argonne and measurements performed with reaction products validate the simulations. So far, an efficiency of 20% has been achieved and the decrease in extraction time with an electric field has been demonstrated to be in good agreement with predictions. Scaling to higher pressures does not present significant technical problems.

One issue of importance in IGISOL type systems is the amount of ionization created in the gas by the primary beam. Studies show that the efficiency of IGISOL systems start to decrease when the amount of energy loss in the gas exceeds a value between 10^{16} and 10^{19} eV/cm³. The ionization densities, even at 100 kW of primary beam power, are far below this. For example, with 100 kW of ¹⁸O beam to produce ¹⁴Be yields a total of about 7.2×10^6 pps entering the cell from the magnetic separator system, a large fraction of them ¹⁴Be. Each particle will deposit about 70 MeV of energy in the cell resulting in a total energy deposition of 5×10^{14} eV over a volume of about 1200 cm³ for an energy deposition density of about 4×10^{11} eV/cm³. This is orders of magnitude below the levels where IGISOL systems show limitations. This is due to the total elimination of the beam at the cell and, in fact, even using the simplest separator described earlier would make the numbers worse by only a factor of ~30 or so, still maintaining the cell within safe operating parameters for cases where the primary beam is not too close to the fragments of interest.

Design of the ion guide/beam formation

The ions extracted from the gas cell will first be channeled by an rf quadrupole structure through a section of differential pumping to an acceleration region where the acceleration can take place unhampered by the residual pressure from the gas cell. This is a standard technology demonstrated at IGISOL facilities and at Argonne and results in much better emittance for the extracted beam.

Two specific examples

To illustrate the capabilities of the proposed scheme two specific illustrative examples have been worked out. The first case is the production of ¹⁴Be from the fragmentation of a 100 kW beam of 100 MeV/u ¹⁸O. In that case, the optimum target thickness is 1.1 g/cm² of Li. With this target, a yield of 1.2×10^7 ¹⁴Be/s is obtained at the end of the separator, together with a similar amount of other isotopes (mainly ¹¹Li). The extraction efficiency out of the gas cell will be in excess of 50% (this has been demonstrated for IGISOL system when the ionization density in the gas is low and 20% has already been demonstrated in the first tests with an accelerated gas cell at Argonne) which can give a final yield of 5×10^6 ¹⁴Be/s available for acceleration. In this case, the 10% momentum acceptance of the separator limits us to a fairly thin target because of the large difference in stopping power between the primary beam and the fragments of interest and the yield at the back of the separator is only 22% of that which would be obtained in a stopping (thick) target. This is one of the worst cases for the separator but still gives a yield which is at least four orders of magnitude higher than is expected for standard ISOL techniques — scaling up the best ISOLDE values to 100 μ A protons. As mentioned in the preceding text, in this case the total ionization in the gas is around 4×10^{11} eV/cm³, orders of magnitude below present operating parameters for IGISOL systems.

Similarly, the production of ⁴⁴S from the fragmentation of a ⁴⁸Ca beam on a 0.6 g/cm² Li target gives a total yield at the end of the separator of 2.1×10^7 ⁴⁴S/s, corresponding in this case to 65% of the thick target yield. About 10^7 ⁴⁴S/s are to be expected at the exit of the gas cell for

acceleration. The gas cell will be bombarded by a total of about 2.8×10^8 pps, a number dominated by the isotope ^{45}Cl . The total ionization in this case will approach 1.4×10^{13} eV/cm³ at 100 kW of ^{48}Ca beam power, still well below present operating IGISOL levels.

Using the best values seen at ISOLDE and extrapolating to 100 μA protons yields a few hundred/s of ^{14}Be . No ^{44}S beams have been reported from ISOLDE because of the chemical activity of sulfur.

Beam intensities expected for this concept for other beams are given as part of the ANL ISOL beam list.

Physics research enhancement

The advantages of using the fragmentation technique with a gas stopper are that it allows a rather uniform efficiency in shepherding ions from production to the acceleration process. This allows the production of beams of elements that are very difficult to extract from the usual ISOL target because of their refractory properties or because they are chemically very active. Over half the elements in the periodic table fall into this category. In addition, the delay times will be short, so that the technique will be especially effective for the shortest-lived isotopes of any element. The following gives examples of the incremental physics to be carried out with this technique, organized along the thirteen physics topics of the "White Paper on Scientific Opportunities with an Advanced ISOL Facility". Most specific examples requiring refractory elements were not included in the White Paper because, at that time, beams of these elements were considered inaccessible to the ISOL method.

1. *Rapid Proton Capture Process* Stopping in a gas cell is ideal for capturing nuclei on the proton rich side of the s-d shell nuclei, and many of these are not readily amenable to extraction from a solid target; for instance ^{14}O , ^{15}O , Si, P and S isotopes. $^{14,15}\text{O}$ provide the break-out from the CNO cycle, ^{24}Si is a waiting point, and nuclei around it are important too. $^{28-30}\text{S}$ are important in reactions towards ^{34}Ar , the next waiting point. Beams of ^{45}V are needed to measure capture leading to ^{46}Cr . Understanding the abundances of $^{92,94}\text{Mo}$ and $^{96,98}\text{Ru}$ require capture cross sections on isotopes on the proton-rich side of these and neighboring refractory elements. ^{24}Si illustrates the point, that since it has a half-life of less than 1 second, it could not be obtained in any useful intensity with solid production targets, while the efficiency with a fragmentation reaction would be high.

2. *N = Z Nuclei* The yields of nuclei at $N = Z$ begins to be small above $Z = 40$. Of the ones that are accessible, and where one would like to have beams of sufficient intensity to do reaction studies, the majority present severe extraction difficulties. In particular, ^{68}Se , ^{78}Y , ^{80}Zr , ^{82}Nb , and ^{84}Mo , are all in this category. The biggest knowledge gap is for ^{80}Zr and none of the isotopes beyond this can be made with ISOLDE type targets. Measurements needed are single nucleon transfer/pick up to determine single-particle structure, but also high-resolution studies of collective excitations.

3. *Doubly-Magic ^{100}Sn* Fusion with ^{54}Ni and/or ^{63}Ga beams and have been suggested to get close to ^{100}Sn . Beams of **Cd, Ag, Sn, Sb**, close to ^{100}Sn , are needed for determinations of the single-particle structure from light ion reactions to better understand the underlying shell structure.

4. *Proton Drip Line* In addition to the $N = Z$ nuclei above, **Sb, Te and the rare earths**, essentially all elements from atomic number 57 to 77 are difficult to extract from a solid target. These constitute the major fraction of isotopes near the proton drip line, including the ones where deformation is likely to be large. Reaction studies on such nuclei are very interesting. ^{48}Ni and its neighbors cannot be extracted with good efficiency from solid target.

5. *Slow Neutron Capture*

6. *Symmetry Studies* Francium itself is not reached with fragmentation. However, for studies of fundamental interactions nuclei such as ^{30}S , ^{54}Co , ^{10}C , ^{66}As , etc. are all likely to be of substantial interest.

7. *Heavy Element Studies* The success of the production of very heavy elements has depended heavily on the combination of stable projectiles and targets. Also, many nuclei can only be made with a neutron excess that is less than optimal for maximum stability. With the possibility of intense beams of nuclei for such studies the selection of particular beams may be crucial for making particular regions of stability with the available (stable) targets. With a ^{208}Pb target beams of neutron-rich isotopes of germanium are needed to reach $Z = 114$ nuclei of the greatest stability, and ruthenium for $Z = 126$. Both of these are difficult to extract from target material and easy when prepared by fragmentation. More generally, beams such as $^{38-40}\text{S}$ (or heavier), $^{49-52}\text{Ca}$, $^{65-68}\text{Ni}$ become very attractive.

8. *Fission Limits*

9. *Nuclei with Large Neutron Excess* These experiments will often be done best with fission products, except in fairly light nuclei. Here high-resolution studies of nuclear structure, inelastic processes, transfer reactions, moment measurements etc. can be done on $^{38-46}\text{S}$, $^{>32}\text{Si}$, Mg's . Studies of shape coexistence in $^{98-104}\text{Pd}$, $^{100-104}\text{Zr}$, $^{100-106}\text{Sr}$ etc. and of gamma-soft nuclei near ^{90}Ru ^{110}Mo are further examples.

10. *Rapid Neutron Capture (r-process)* Here it is especially important to have the capability of carrying out measurements on "waiting-point" nuclei over a wide range of species, including neutron-rich isotopes of **Fe, Co, and Ni, Pd and Cd**. The lack of chemical sensitivity is important in being able to study whichever elemental species are required to test the models of this process.

11. *Doubly Magic Nuclei* An example of such a nucleus may be ^{44}S which has 28 neutrons and 16 protons, the closure of the $sd_{5/2}$ subshell, or ^{68}Ni . For both nuclei the exploration of the level structure in the vicinity will supply crucial information on the shell structure in weakly bound systems.

12. *Weakening of Shell Structure* Here again good beam intensities in the most neutron-rich nuclei with closed proton shells are particularly desirable. Except for Ca and Sn, closed protons shells or subshells occur in **Si, S, Ni, and Zr**, all elements that are difficult to extract.

13. *Halo Nuclei* Many interesting halo nuclei are produced with orders of magnitude enhanced yield utilizing the gas stopping technique. ^{14}Be is a prime example of such a nucleus that can be produced copiously with fragmentation reactions. This nucleus is one of the most fragile of halo nuclei and its study with high-resolution beams could prove extremely valuable for this field. Many other examples exist in the lighter nuclei where fragmentation reactions are favored, and where the elements are either refractory or chemically active so that their extraction in a short time is not practical.

Schematic Layout of Fragment Separator and Gas Catcher

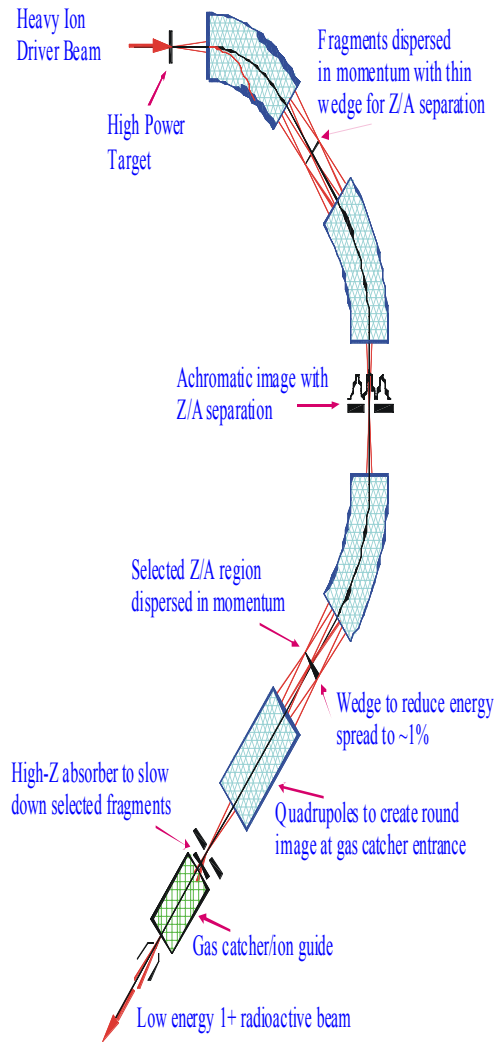


Fig. 1. Schematic Layout of a Fragment Separator to collect heavy ion fragmentation products and deliver them to the gas catcher/ion guide apparatus.

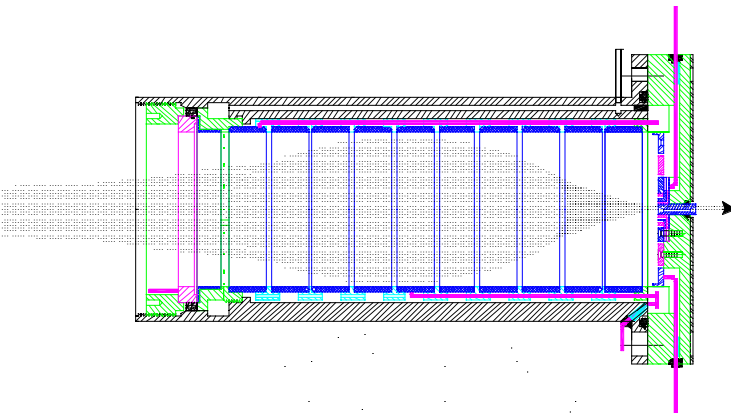


Fig. 2. Drawing of the test gas cell used at Argonne to successfully demonstrate the use of RF and DC extraction fields inside the cell to guide the ions to the exit aperture. [Expanded view of the gas catcher/ion guide at the bottom of Fig. 1 above.]